UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

POLYTECHNIQUE MONTRÉAL
UNIVERSITÉ D'INGÉNIERIE

DEGREE FINAL PROJECT

TFG TITLE: Experimental study of diphasic flow during the injection stage of composite processing

DEGREE: Aerospace Systems Engineering, Air navigation specialty

AUTHOR: Júlia Blanch Sánchez

ADVISOR: Prof. François Trochu

SUPERVISORS: Prof. Cédric Beguin and Dr. Philippe Causse

DATE: 30 de maig de 2019

Títol: L'estudi experimental del flux difàsic durant l'injecció en la creació d'un material compost
Autor: Júlia Blanch Sánchez

Director: Prof. François Trochu

Supervisors: Prof. Cédric Beguin and Dr. Philippe Causse

Data: 30 de maig de 2019

Resum

Les bombolles porten estudiant-se fa més de 20 anys. En el sector aeronàutic, aquestes bombolles apareixen durant la injecció per la creació d'un material compost quan l'aire es queda atrapat. Per a que una peça aeronàutica sigui certificada, ha de tenir menys d'un 2 % de cavitats.
Per tant, en aquest projecte, es fa un estudi experimental del flux difàsic durant la injecció en la creació d'un material compost. Aquest es duu a terme mitjançant la tècnica d'injecció al buit on s'han estudiat els diferents tipus de configuracions, per tal de trobar la més adequada sense gaires riscos a fuga. A continuació, s'han creat fibres òptiques de punta cònica amb àcid HF, per la detecció de bombolles durant la injecció, on s'ha hagut de tenir molta cura durant el procés de seguretat i creació d'aquestes. Seguidament, la fusió entre fibres ha sigut desenvolupada per tenir connexió amb l'oscil·loscopi i els ordinadors que recullen la senyal que ens mostra el làser. Al mateix temps que el recolliment de dades del làser es feia, també es gravaven instantànies amb la càmera, que més tard es processaven amb codi Matlab per a obtenir un vídeo de les imatges. Com es recollien les dades i imatges al mateix temps, això facilitava una millor la interpretació del que estava passant en cada moment amb les bombolles. Un cop processada la informació es van dividir els tipus de senyal i es va veure quantes bombolles podíem detectar en 1 minut per veure si totes les que detectava el làser eren les mateixes que veiem al vídeo. El programa Matlab ens permet veure com ha sigut la detecció i en quin segon, des de que el làser ha estat encès, podem veure la bombolla en el vídeo.
Per altre banda, un codi Python s'ha realitzat per dibuixar les trajectòries de les bombolles fins arribar a la punta de la fibra. Una de les coses que es van arreglar foren les diferents intensitats de llum que tenien cadascuna de les instantànies que es van igualar amb la mitja d'intensitats. A més a més, també es va fer la mitjana de 500 imatges, per tal de tenir un fons llis on dibuixar el camí de les bombolles. Finalment, algunes conclusions i millores es van proposar per a la continuació d'aquest treball en un futur.

Paraules clau: material compost, cavitats, flux difàsic, injecció al buit, fibres òptiques, punta cònica, àcid HF, bombolles detectades.

Title : Experimental study of diphasic flow during the injection stage of composite processing
Author: Júlia Blanch Sánchez

Advisor: Prof. François Trochu

Supervisors: Prof. Cédric Beguin and Dr. Philippe Causse

Date: May 30, 2019

Overview

The bubbles have been studied for 20 years. In the aeronautical sector, these bubbles appear during the injection for the creation in a composite material when the air is entrapped. For an aeronautical part certification, less than 2 % of voids is needed.
In this project, it is developed the experimental study of diphasic flow during the injection stage of composite processing. It is applied the vacuum injection to realize it and different set ups have been studied in order to find the more suitable one with the less leakage probability. Then, optical fibres with a conical tip (treated with acid HF) have been created carefully to detect the bubbles during the injection. After that, a fusion between fibres to obtain a link with the oscilloscope and the computer was required to see the signal of the laser. At the same time of the data recording, the camera frames were captured. Later with a Matlab code the frames were unified to achieve a video. As the recordings was at the same time, it was easier to interpret what was happening at every moment with the bubbles. Once all the information was processed, the different types of signals was divided. Then, the data signal and the video acquisition were compared to see if the bubbles detected was the same number as in the video. The Matlab code permits to see how the detection has been done and at which second the bubble appears in the video, since the laser was turned on. On the other hand, a Python code has tracked the trajectories of the bubbles until arrive to the tip.
Somethings could be improved but some of them was fixed as the different intensities in the different frames. An average of intensities was calculated and applied in of the frames to obtain the equal light in all the video. Furthermore, an average of 500 frames was done in order to obtain a background without bubbles to track the trajectories. Finally, some conclusions and improvements have been proposed to continue the study in a future.

Keywords: composite material, voids, diphasic flow, vacuum injection, optical fibers, conical tip, HF acid, bubbles detected.

To the department of
composites and optical fibers
of École Polytechnique de
Mont-Réal for all the support.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The composite materials have improved the aeronautical sector since its application. These materials have made airplane's weight decrease, an improvement of the benefits and characteristics of the materials (high mechanical and fatigue resistance, rigidity), and higher range/time of flight. Nowadays, the composite materials represent a bigger percentage of the total airplane structure as for example in B787 Dreamliner that represents the 50% of the total airplane. There are some methods to create these materials such as, vacuum injection. In this technique, when the matrix is injected in the fabric of fibers, some bubbles of air are formed. In order to improve the quality and properties of that, it has been studying for more than 20 years the bubbles that appear during the injection to avoid cavities in its solidification. The voids produced once the curing is realized, makes the material more fragile. For this reason, the aeronautical pieces are certified only with a less than 2% of voids. This regulation is established to preserve the security, safety and efficiency of the materials and of all the structure of an aircraft.

To be able to avoid them, a long study has to be done. Some people have started with a research similar to this, applying different type of sensors. To understand the flow behavior a few parameters have to be taken into account as for example, the changes of: pressure, heat, size, velocities...

One of the sensors which permits the study are the optical fibers. They are widely used for communications, because these sensors allow transmissions over longer distances and at higher data rates rather than other forms of wired and wireless communications. They are also used as sensors, and in a diversity of other applications. If they are adapted as sensors, they are able to measure strain, temperature, pressure, and other parameters. Furthermore, the optical fibers can be put in service as a low-cost laser to detect bubbles giving us information about the size and the velocity of that. To know how the flow is varying during the injection, the idea is to apply some of this optical fibers along the set up. But before, the study has to be performed with only one to see if it works and if can give the information expected.

CHAPTER 1. BACKGROUND

The composite materials have been studied during a lot of years and they have a big impact in the aeronautical sector, mainly saving money and weight. To understand the development and the technical aspects of this project I would like to introduce some concepts and facts to make easier the comprehension.

1.1. Composites materials

1.1.1. What is it a composite material?

A composite material is a type of material composed by a matrix and fibers. This type of materials could be created with two or more materials. The purpose is the creation of a final material with a better properties than we had before. So, we have to choose the materials according with the properties that we want to obtain at the end. The properties can be improved in a different ways: chemical, mechanical or physical.

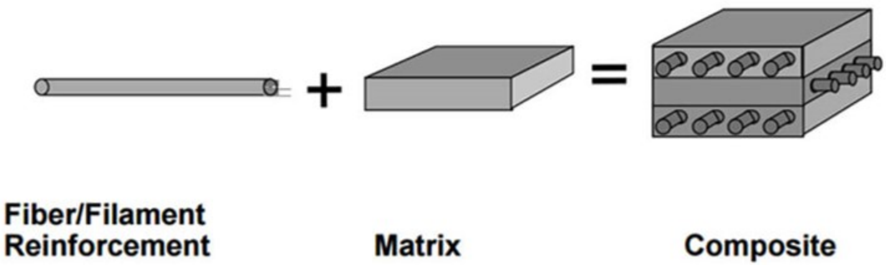


Figure 1.1: Composite material

1.1.2. Types of manufacture

To achieve a composite material there are different types of methods of manufacture them [1]. The typical and important ones are described then.

1.1.2.1. Liquid composite moduling (LCM)

This type of manufacturing consists in the application of a liquid matrix on the fibers to impregnated them. And once the liquid is solidified, the composite material is created. The fact is that we have different methods to impregnate these fibers.

- Resin transfer moduling (RTM): To apply this method, it is precise to create a mould where we are going to put the fibers. Once we have put the fibers inside the mould we have to close it and inject the matrix. The mix will be compressed in order to be ensure that the fibers are impregnated. After that, we have to wait for a while.

At the same time, we are going to put the mould inside of an oven where the temperature will reach the 200 degrees and will be there for 20 minutes and then the temperature will decrease again until the 121 degrees. When we retire the mould, this will be cold and the matrix will be solidified.

- Vacuum infusion: This method is preferable for larger parts. The first step is to construct a configuration with an inputs and outputs to make the injection. These inputs and outputs have to be well situated in order to avoid some dry parts in the fiber structure. Also, the structure has to be simplified as much as possible to prevent the leaks in the vacuum part and to make easier the resolution in a leak case. When the structure is constructed, a vacuum bag is put on the top and we have to ensure that a perfect vacuum is done. Then, the injection is done to impregnate the fibers and at the end the output will be waiting the not impregnated resin.

1.1.2.2. Consolidation process

The consolidation process is preferable to be applied when you want to assembly small pieces into a single product. The process consists in recover a mold with prepregs layers maintaining the accurate orientation of the fibers. After the lamination process and putting the mold in a vacuum bag to try to avoid entrapped air, the mold is put in an autoclave to realize the cure and the consolidation. The autoclave permits to maintain a certain pressure and temperature inside of the chamber. So, the external pressure applied to the material makes the vacuum inside of the bag doing a properly consolidation.

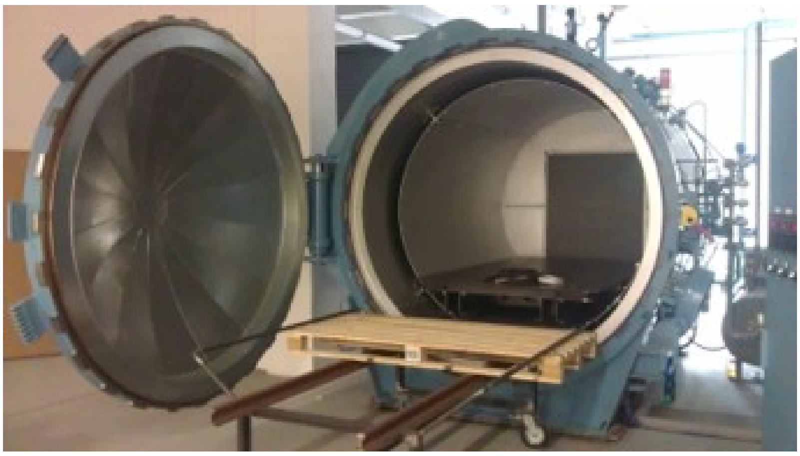


Figure 1.2: Consolidation process

1.1.3. Which is the objective to apply it in aeronautics?

The aeronautical parts need to have the acquired mechanical and physical properties in order to make the structure of the aircraft safely, light, compact, efficient and resistant. So, to obtain all the required properties we have to mix some materials that contain the expected properties.

Nowadays, a lot of parts in the airplanes are made of a composite materials and also the engineers are studying some other kind of composites to try to improve and achieve a better ones. The last innovation in this ambit is the application of composite materials in a fan like in the Figure 1.3.

Figure 1.3: CFM LEAP 2016

1.2. Architecture of the fibers

The fibers could be positioned in different ways. The architecture of the fibers is interesting because you can find different properties changing it. We can see in the Figure 1.4 some examples of kinds of architectures.

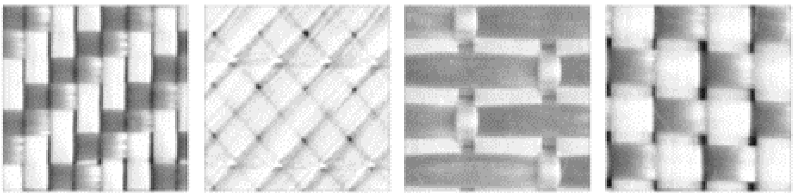


Figure 1.4: Types of architectures

As we can see in the Figure 1.4, the fibers has different directions. This fact creates distinct sizes of spaces between tows called scales.

1.2.1. Dual scale architecture

In the Figure 1.5 it is shown that in the fiber architectures appear two types of scales, mesoscale (or macroscale) and microscale.

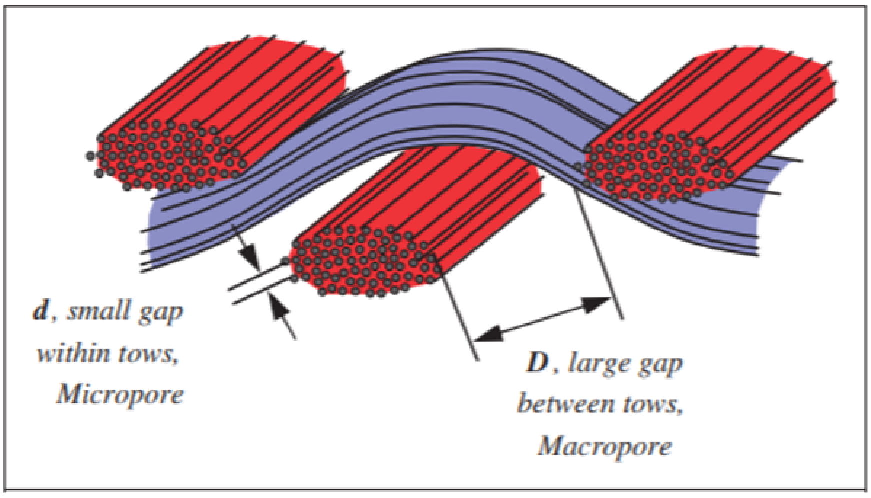


Figure 1.5: Macroscale and microscale [3]

The macroscale is the bigger space situated between the tows and microscale is the small space inside of the tows. This can be bigger or smaller depending on the manufacture and architecture that you have chosen to your fibers. These scales will have a big impact on the final properties and structure of the piece.

1.3. Voids

The two scales, of the previous section, make pores. These ones can create voids in the creation of composites when the matrix is solidified.

1.3.1. Type of voids

If we classify the voids for their size, we can distinguish 3 types of voids: dry spots, macrovoids and microvoids.

1.3.1.1. Dry spot

Dry spots appear when the injection of the matrix has been done in a wrong way and not all the fibers has been impregnated. When this happens and the matrix is solidified and there are big voids because of the composite has not been realized in all the parts of the fibers. The main reason or cause of this voids are for the inappropriate placement of the inlet/outlet.

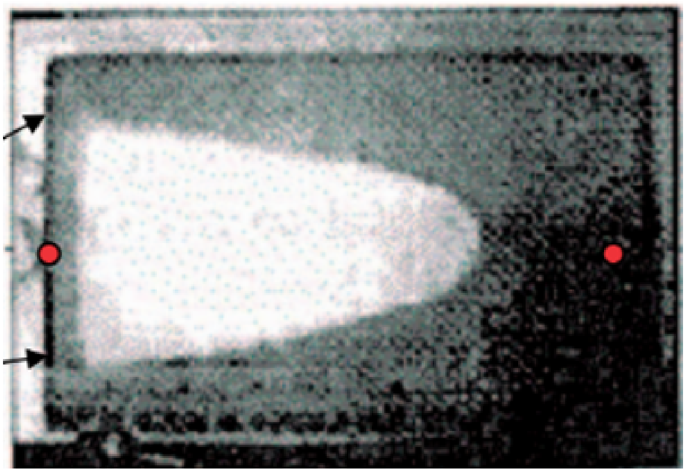


Figure 1.6: Dry spot [3]

1.3.1.2. Macrovoids

These type of holes are smaller than the dry spots, but also are important for the final result of the composite. The macrovoids appear between the tows because of the macropores. It occurs when the flow velocity reaches the vents before to be impregnated in the fiber. Also, it can appear when the vacuum is not perfect or when the pressure around the dry zone it is not enough or decrease.

It can be reduced or completely avoided by some methods:

- Leave the impregnation enough time to be ensured that all the fibers are wet.
- Controlling frontal flux with sensors.
- Predict the macrovoids formed during the injection.

On the one hand, in the figure 1.5 are represented as the cote D. On the other hand, as we could see in the Figure 1.7 these voids are represented inside of a fabric [3]. The size of the voids is of 10μm$\sim$1 mm.

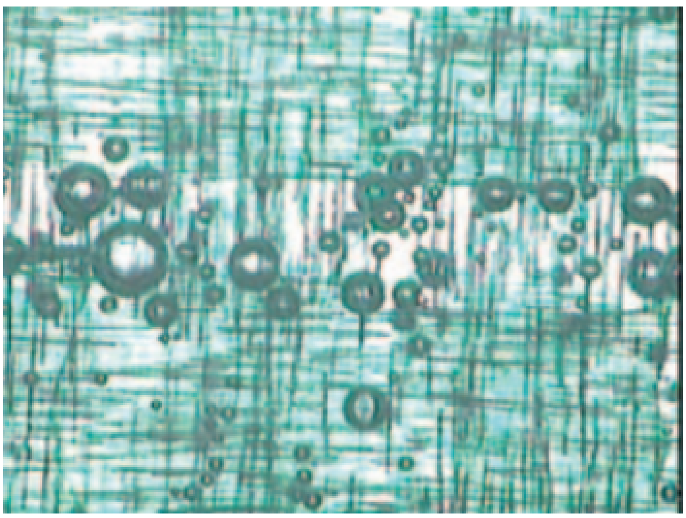


Figure 1.7: Macrovoids [3]

1.3.1.3. Microvoids

Microvoids are the smallest holes. They are created when the air is entrapped between the fibers, within the tows. These voids make some difficulties to determine the flow front.

In the Figure 1.8 are pictured in a real experiment [3]. The size of these voids it is between 1$\sim$10μm (as the Figure 1.5 shows in cote d).

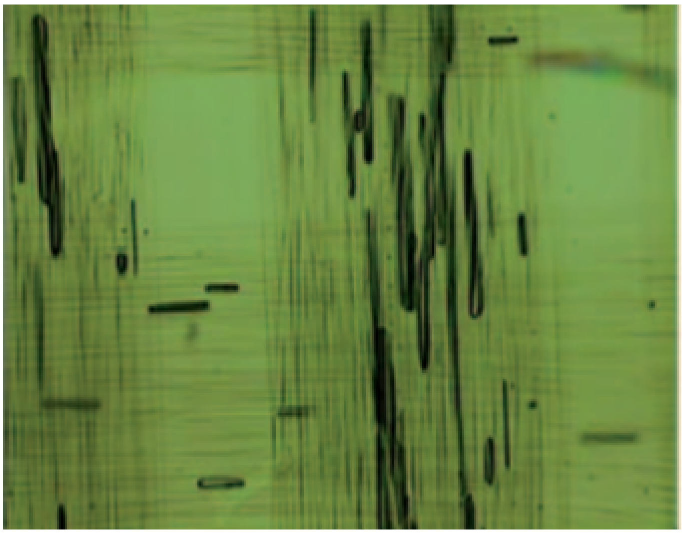


Figure 1.8: Microvoids [3]

1.3.2. Creation of voids

According with the previous section, the creation of the void could be for a different causes.

On the one hand, we have the dry spot case that is because the entrance and the exit of the matrix are not well positioned. So, we have to study different configurations of the positioning and be ensured that all the parts, zones, regions will be impregnated of the matrix.

On the other hand, we have macrovoids and microvoids that are created for the different velocities between tows as is reflected in the Figure 1.9.

The case of macrovoids is the picture b) and d) (in the Figure 1.9) where the velocity is slower than in the picture a) and c) (in the Figure 1.9) where we reflected the microvoids within the tows because of the higher velocity.

The pictures a) and b) provide us a view from the top of the material. Otherwise, the c) and d) provides us a profile view.

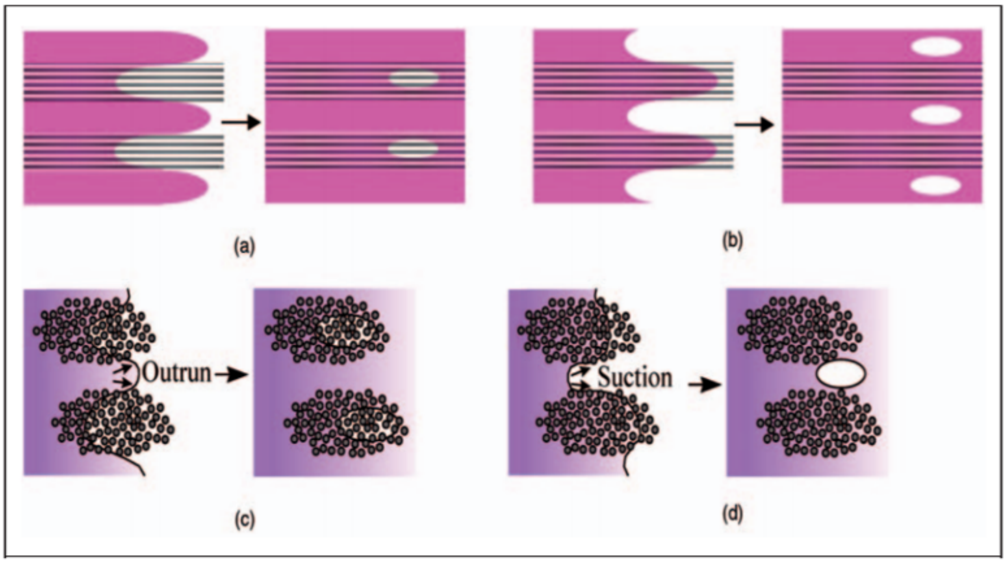


Figure 1.9: Creation of voids [3]

1.3.3. Behavior of voids

After the void is created, the size and the form vary during the time because the pressure of the resin next to the void increase and the air inside of the void is compressed. So, we can use the expression of the ideal gases because the forces are equilibrated. It is important to take into account:
- The void form is always the same.
- The pressure of the resin and the pressure of the bubble are equilibrated by the Surface tension.
- Finally, the capillary pressure has to be situated under the Surface tension.

We can define the behavior as the following expression, where we find the pressure inside of the bubble, the capillary pressure, the pressure of the resin and the volume of the bubble.

$$V_v = \frac{P_{int} + P_c}{P_v + P_c} \cdot V_{int} \tag{1.1}$$

- V_v: Volume of void.
- V_{int}: Initial void volume.
- P_v: Pressure inside.
- P_{int}: Initial air pressure inside the void.
- P_c: Capillary pressure.

1.3.4. Modelling of voids

The diverse type of voids are modelled in a different ways. So, each type has its own expressions detailed in [3].

1.3.4.1. Dry spot

There are some expressions that help us to understand the behavior of the voids. This expression correspond to Darcy's law.

$$\overrightarrow{v^D} = -\frac{\widetilde{K}}{\mu} \cdot \nabla P \tag{1.2}$$

If we consider an incompressible flow and mass conservation that requires that the gradient of the velocity is equal to 0.

$$\overrightarrow{\nabla v^D} = 0 \tag{1.3}$$

This means that the Darcy's law integrated into mass conservation incompressible flow it is equal to zero too. So, we obtain the following expression.

$$\nabla \frac{\widetilde{K}}{\mu} \cdot \nabla P = 0 \tag{1.4}$$

With the previous expression, we are able to localize the best places to inject the resin in order to avoid the dry spots.

1.3.4.2. Macro and Microvoids

The situation is a little bit more complex if we want to model the microvoids and if we want to know how much quantity of voids are in the piece. To achieve this, we have to take into account all the parts of the parts of the composite. The fully impregnated parts, the parts where we can find the voids and the part that in not impregnated. These three regions are reflected in the next Figure 1.10.

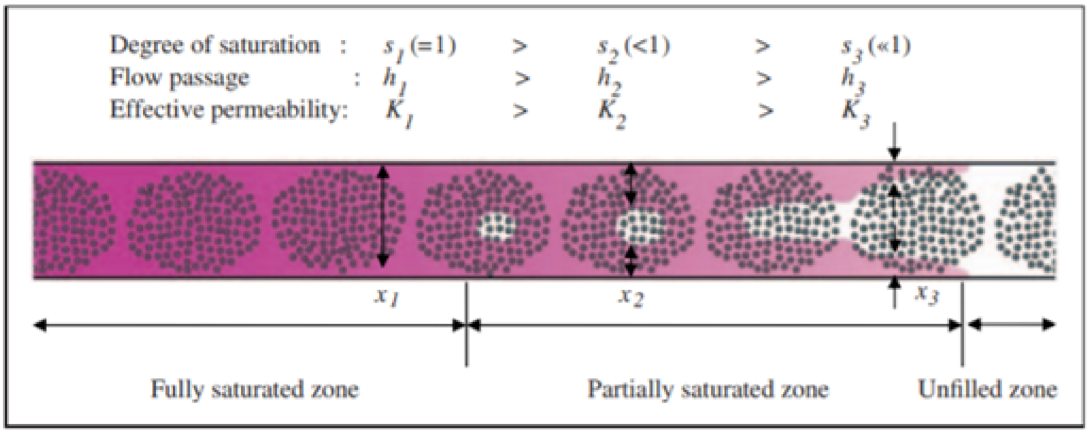


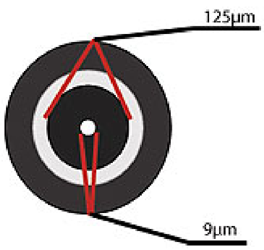
Figure 1.10: Impregned regions of a composite [3]

So, as we can see represented in the Figure 1.10 the first part is without any void and we are going to call this part fully saturated zone. The region with some voids is the partially saturates zone and the region that is not still impregnated is unfilled zone.

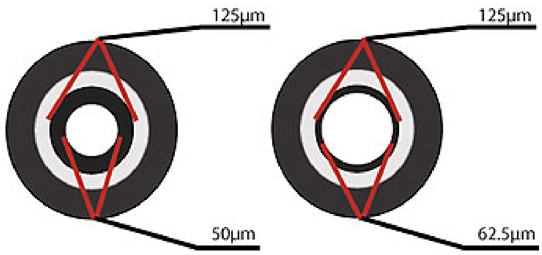
As in the dry spot case there are some expressions that reflect the situation. That are more complex and appear in the article by Park and Lee in [3].

CHAPTER 2. OPTICAL FIBERS

These type of fibers are so flexible, transparent and recovered of plastic or glass with a diameter of the order of microns. They are used to transmit light between the 2 extrems. The optical fibers are used in comunications to reduce losses, weight and to be able to increase distances and bandwidth. Two types of fibers are found single mode and multi-mode.
- Single mode:Coomunication links longer than 1,000 meters.
- Multi-mode: Wide core diameter and short distance communication links. Required in a missions which high power has to be transmitted.



(a) Structure single-mode fiber



(b) Structure multi-mode fiber

Figure 2.1: Structures of the fibers

2.1. Structure

Optical fibers has a different layers in order to protect the fiber and to avoid the break of that. Typically include 4 layers:
1) The core.
2) Transparent cladding material with a lower index of refraction.
3) A yellow layer called buffer.
4) Jacket is a layer of plastic that makes the final fiber much more resistant.

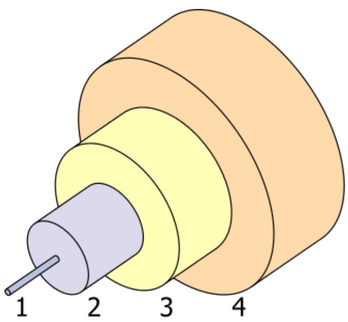


Figure 2.2: Layers of the optical fibers

This structure allows that the light stays inside of the pipe.

2.2. Fusion between optical fibers

To make a connection between two fibers is really important take into account the losses of the fusion. The value accepted for these losses is 0.5dB or less, if it is more the fusion is not valid and has to be done again.

To make it possible a precise alignment of the cores and its coupling is required. So, the method consists in melt the both extremes and unify them. Then a plastic covers the fusion and it is heated to fix and make it more resistant.

These fusions are applied in order to improve the functionalities of the fibers, for example they can actuate as a sensors, lasers, etc. So, if we have a connector we can connect it in the oscilloscope and interpret the signal that the fiber is seeing as the Figure 2.3 shows. Also, in the Figure 2.3 the fusion can be identified because it is recovered by the red plastic and the 2 different fibers are distinguished. One of them has the fourth layer (the Jacket) and the other one only has the buffer.

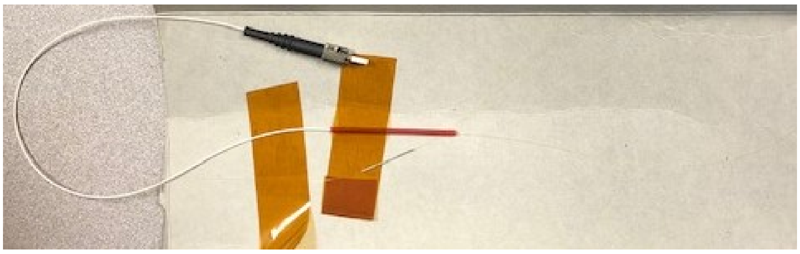


Figure 2.3: Connector in a fiber

An example of a fusion is the Figure 2.4 where it is shown also the losses (that has to be less than 0.5 dB).

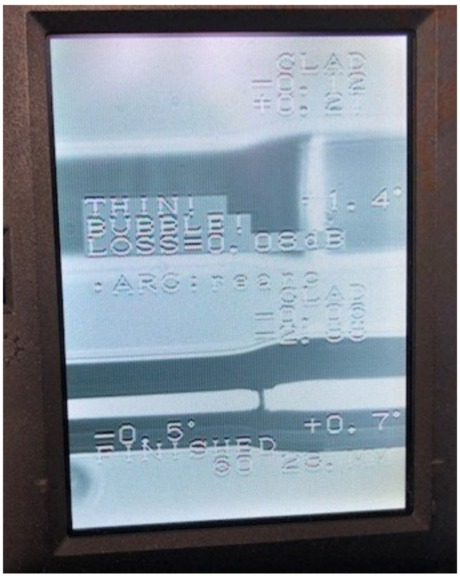


Figure 2.4: Fusion example

2.3. Detection of the optical fibers

The detection of the optical fibers permits the travelling of the light. The light bounces to the walls of the optical fiber. The problem is that if the light bounces with a shallow angles the light is reflected back again. When this happens the glass acts as a mirror (total internal reflection). This fact permits to keep the light inside of the fiber.

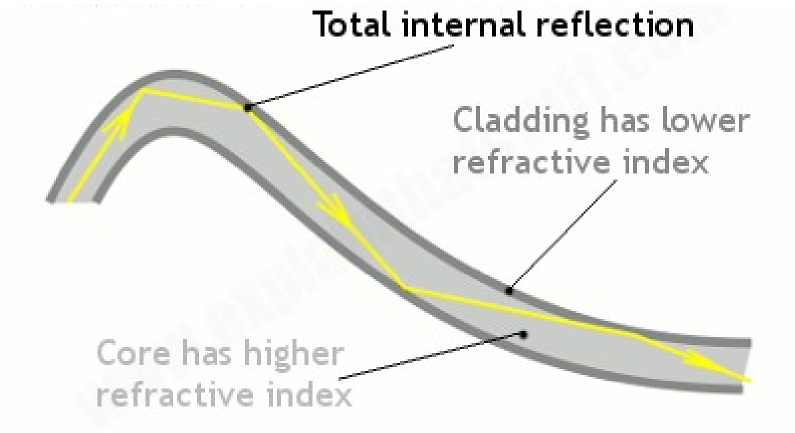


Figure 2.5: Internal reflection of the optical fiber

To detect bubbles it is not enough with the reflection of the light also we need a properly tip that could detect it. A flat clever could not detect the bubbles therefore a conical tip is design. If the bubbles have the same diameter as the optical fiber the detection will be better.

2.4. Creation of a conical tip

The procedure to create a conical tip consists in [4]:
1) Fill a glass with acid HF and then a little bit of silicone oil (the acid HF decompose/desintegrate the fiber).
2) Fix the fiber with a support.
3) Put the fiber inside of the glass.
4) Wait about 30 min.
5) Retire the fiber and see the result in a microscope.

The conical tip enables to detect the bubbles and retransmit it in the oscilloscope. Furthermore, if a computer is connected you can obtain the data of the laser in a txt document and then it could be treated.

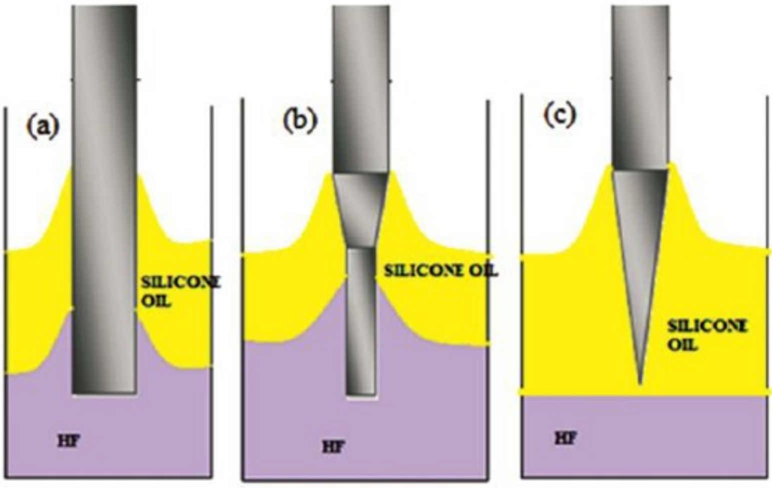


Figure 2.6: Conical tip formation [4]

2.5. Test of functionality of the fibers

To be able to interpret the signal, a fusion between two fibers having a connector in one of the extremes, is required. As it has been annunced before, the connector allows to see the signal, which is detected by the tip, in an oscilloscope. So, in order to validate the functionality of the fusion a test is realised.The test consists in putting the tip inside of a glass of water and see in the oscilloscope how the signal varies with the change of media.

The procedure of the preparation is not complex. Firstly, the signal in the air has to be situated in the positive numbers but under the saturation. Then, the tip is submerged in the water and probably nothing is going to change in the oscilloscope because the adjust of the phase and gain parameters is needed. Once, both of them are with suitable values the signal is going to appear in the screen of the oscilloscope. Every time that a bubble is detected a step is shown in the oscilloscope(as in Figure 2.7).

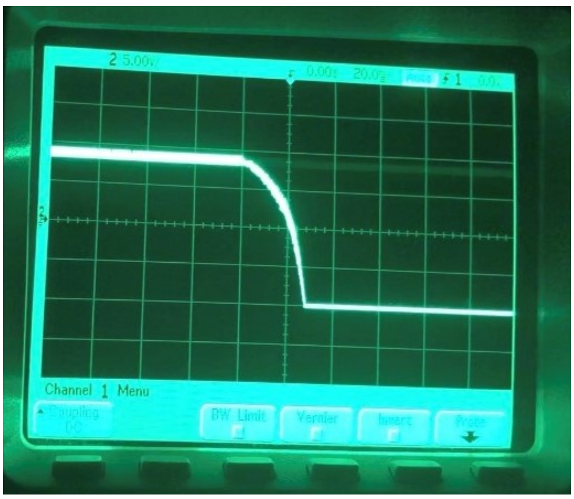


Figure 2.7: A bubble detected by the oscilloscope

The sketch of the representation is in the Figure 2.8 when the tip is in the air is in positive numbers and when it is in the water should be the same number in the negative way.

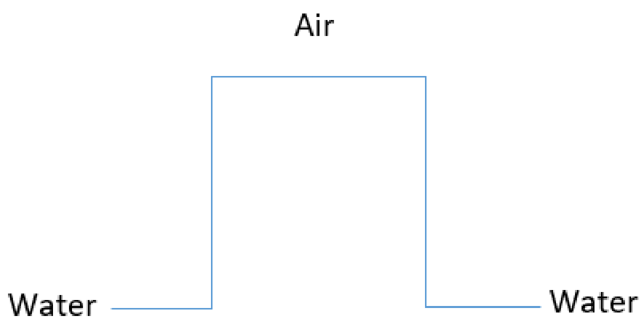


Figure 2.8: Sketch of a bubble detection

As soon as the functionality is tested, the fiber could be applied or used. The test has to be done every day that you start working with one fiber to adjust the parameters.

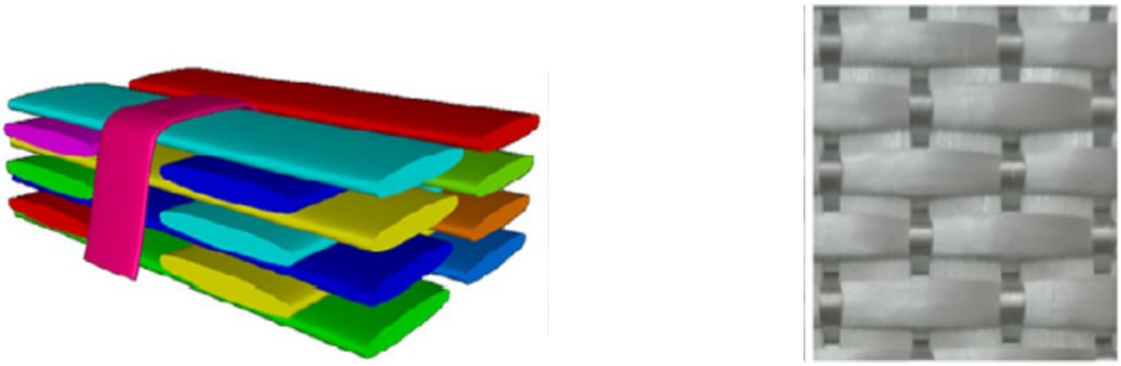
CHAPTER 3. METHODOLOGY

This project started doing a preliminary research about about previous work on the bubbles [2] that appear during vacuum injection, and also on the manipulation of the optical fibers that are used in the experiment (conical tip creation, security protocol with acids, the results of this tip in other experiments, fusion between fibers etc). During the experimental part, also it has been done a research about the experiment realized in this report but with other type of sensors (as [7] [8] [9] [10] [13]) to compare and see which their results are (pressure sensors, temperature sensors, etc). Finally, Matlab and python codes have been implemented to the data and video treatment to obtain results.

3.1. Materials of the composite

3.1.1. Fibers

As it is explained before, the architecture of the glass fibers it is important. The structure that it is applied in this project (pictured in the Figure 3.1)is called 3D orthogonal glass fiber and appear in [14] as a fabric name of TG-96-N.



(a) Structure of the fabric TG-96-N

(b) Architecture of the TG-96-N

Figure 3.1: Structure of the fabric applied

The main characteristics of this structure are explained in the table 3.1 where are indicated the number of columns in each direction, per cm, the density, thickness, etc.

Fabric name	**Fabric type**	**Warp 'nbw'**	**Weft 'nbf'**	**Warp (counts / cm)**	**Weft (counts / cm)**	**Surface density (g/m_2)**	**Thickness (mm)**	V_{f0}
TG-96-N	3D Orthogonal.	3	4	6.9	14.8	3250	2.79	0.457

Table 3.1: Properties of the fabric [14]

3.1.2. Matrix

The matrix of the composite of this project is silicone oil in order to apply resin. In an experiment like that the use of silicone oil has some advantages:
- It is better to see the bubbles in the video acquisition.
- It is easier to clean the set up.
- It is cheaper.
- Easier to work with or manipulate it.

3.2. Lab scale setup for fiber impregnation

The laboratory tests starts with some experiments to find the best vacuum injection setup (technique to make a composite material), considering which was the better positioning for the inlet and outlet in order to avoid dry spots, and which material was the best for our injection table.

The first surface that we had in the experiment was a metal one, as we can see in the Figure 3.2. The inconvenient was that the ”tacky tape” used to fix the vacuum did not stick as it should. So, the metal table configuration was changed because of the complexity and high probability to have leaks. To fix the problems of the last table, the surface was changed for a glass platform where the yellow band adhered much better as the Figure 3.3 shows.

If a comparison between the first set up in the Figure 3.2 and the new one in the Figure 3.3 is done, we can see how it is simplified even thought the new set up is more rudimentary but safer and cheaper (smaller setup, less material). In the first set up, a specific length of the fabric was required (30 cm) in order to be next to the inlet and outlet to have a suitable distribution of the matrix. But in the second table the length of the fabric does not care because the inlet and outlet positioning are not fixed.

Both set ups are composed by:
- A fabric of 3D Orthogonal glass fiber.
- Yellow band.
- Plastic spiral that permits a preferable distribution of the silicone oil.
- Inlet and Outlet.
- Vacuum pump.
- Tank of silicone oil.

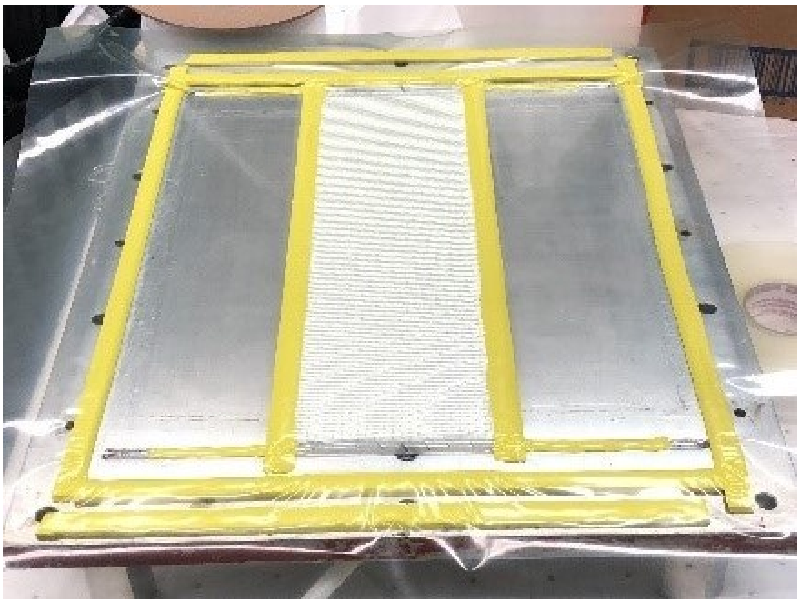


Figure 3.2: Old setup with metal table

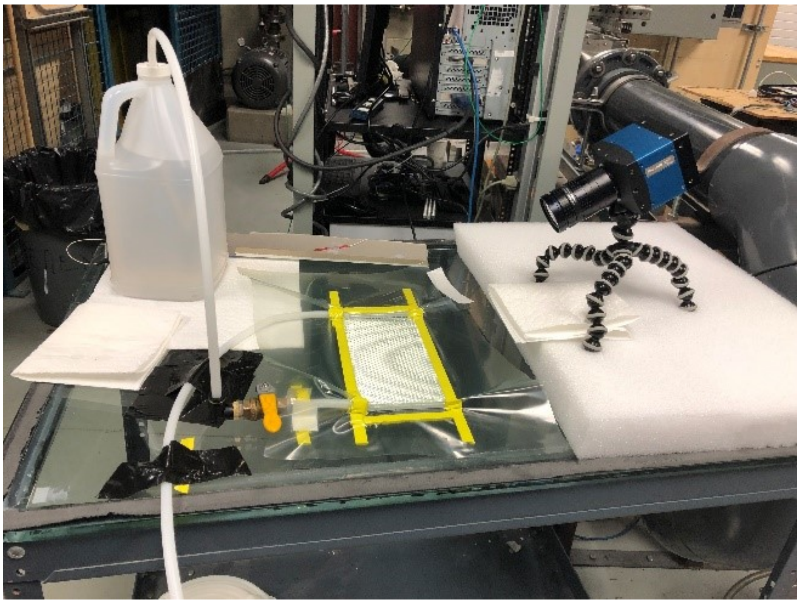


Figure 3.3: New setup with glass table

3.3. Fiber optics to mesure the flow

Then, an acid HF was applied to the fibers in order to disintegrate or decompose it forming a conical tip (Figure 2.6). Once the tip has been created following all the security and protocol instructions [5], the fiber has been fused with another that enables connection to the oscilloscope and be fed to became a laser. The fiber with the connector and the fusion are protected with a plastic layer that makes less fragile the hole fiber. The final mechanism: the tip is a laser that detect the bubbles. At the same time, the signal is projected in the oscilloscope thanks to the connector, a computer records the data and a camera films what it is happening in the injection.

As the Figure 3.4 shows, this is one of the fibers after the treatment with the acid which has been used in the experiments realized to be able to develop the project.

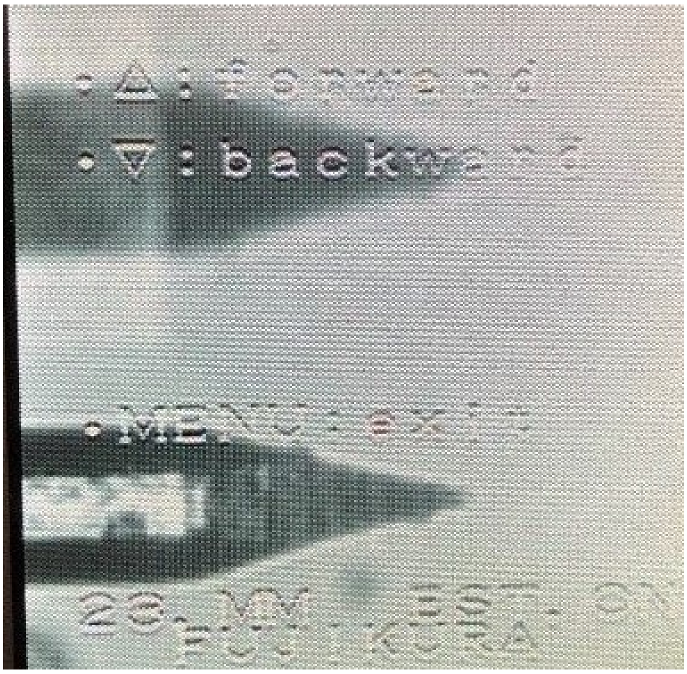


Figure 3.4: Conical tip after the treatment with acid HF

Once the fiber is built, the fusion has to be tested to assess its functionality with the test described before in section 2.5..

Also, some test with optical fibers has been realized to achieve the adequate positioning of the fibers. The first try was with the metal table and with a capillary tube to protect the tip (Figure 3.5). The issue was that the bubbles goes around the tub and the laser did not detect any signal (for the next experiments the capillary tube was removed).

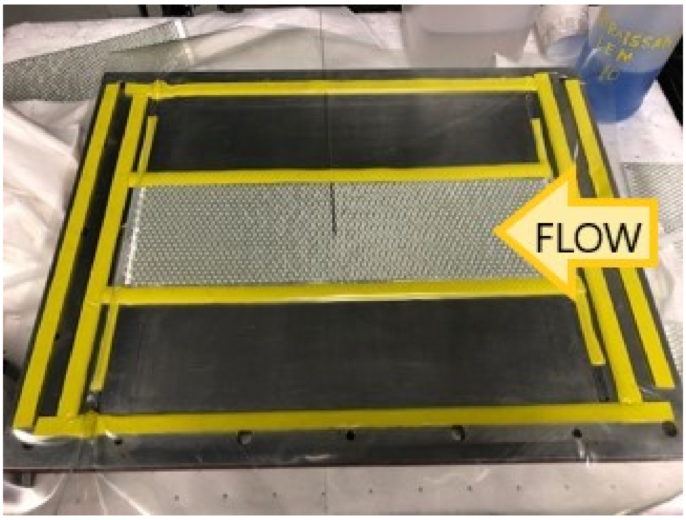


Figure 3.5: Positioning of the fiber with the capillary tube

After the last experiment, the positioning of the optical fiber was changed. The second location of the fiber was parallel to the flow but in the opposite sense (Figure 3.6). The problem of that locality was the difficult precision to situate the tip.

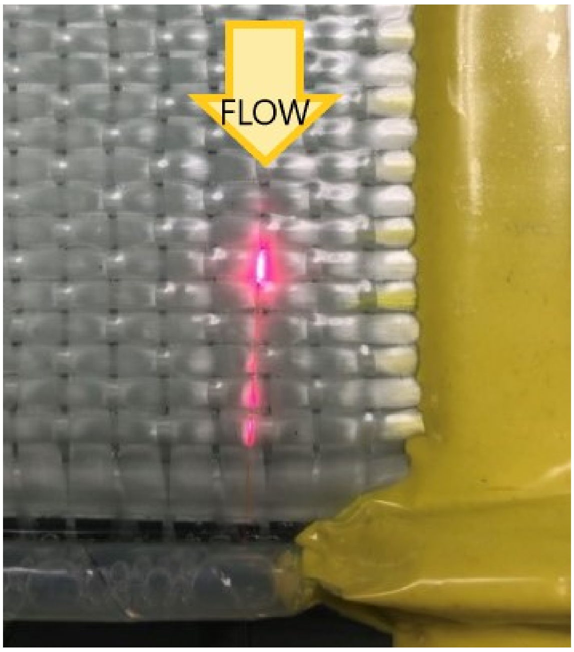


Figure 3.6: Difficult positioning of the laser to achieve good results

Finally, the idea was to rotate the fabric and not the laser because high precision was not required and the number of bubbles recorded was higher (Figure 3.7). This is because the trajectory of the bubbles this time is straight on and they do not have to cross between the tows of the fabric. So, the bubbles are visible all the time in the same line (facile to follow their routes).

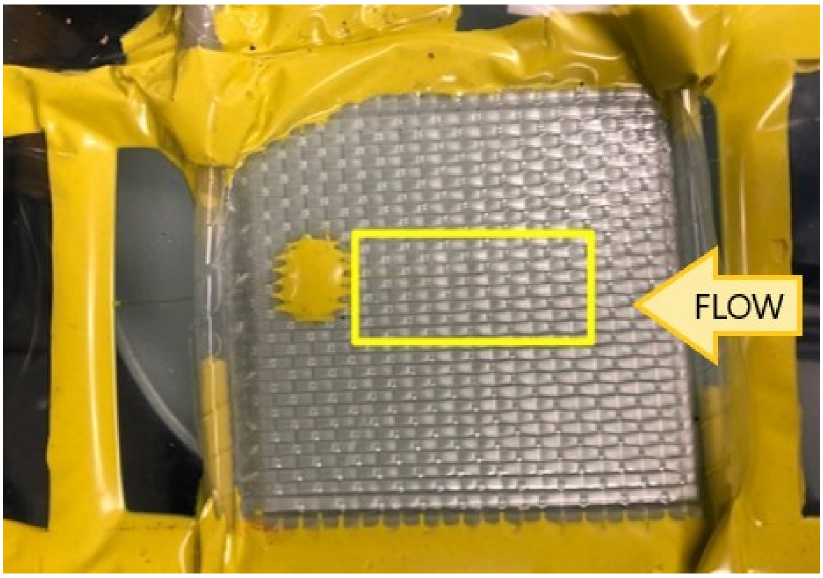


Figure 3.7: Good positioning of the fibers and easier to detect the bubbles

This configuration permits to record a good data to analyze and treat it with Matlab code. Also, this trajectory of the bubbles permits to delimit the area in the video acquisition and make it effortless the bubbles detection because are visible all the time (do not cross within the tows).

3.4. High Speed Video Acquisition

Finally, after some tests, the data and camera records have been taken at the same time to be able to see what is happening during the injection and interpret it in the plots of the data results.

Before to start any test, the gain and the phase have to be readjusted because the liquid now, it is silicone oil and the parameters will be slightly different (than they was with the water). Also, in the data records has been adjusted also the frequency and the number of samples to have a good data (without so much points that are not needed). Furthermore, the camera has to be tested in some injections before the good one, to determine which light and location the camera is able to see the bubbles better.

Figure 3.8: Mikrotron MotionBLITZ Cube 4

The camera used is Mikrotron MotionBLITZ Cube 4 (Figure 3.8) with a frequency used of 198Hz, makes frames and do not record a video. To be able to see it like a video another Matlab code has been precised. The problems with the light was because the camera only records in black and white. So, the light was an important fact to be capable to see fitly the bubbles in the laser detection. The final positioning of the camera was with the support of the Figure 3.9 where a hole was done to fix the camera (Figure 3.10).

To improve the visibility of the bubbles, the light was under the table of glass pointing directly to the fabric (same direction as the camera but in the other sense).

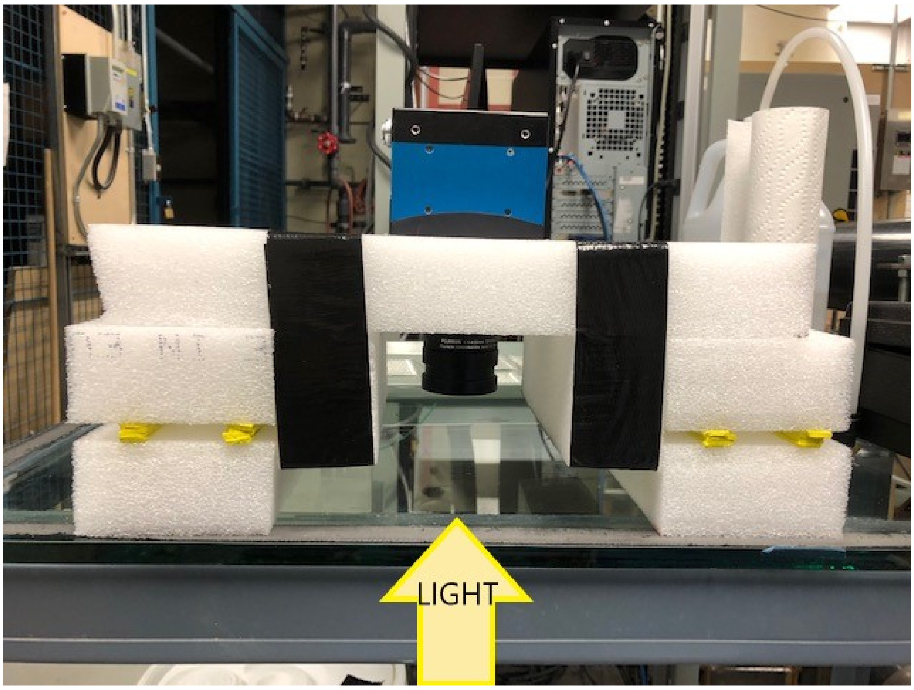


Figure 3.9: Camera support

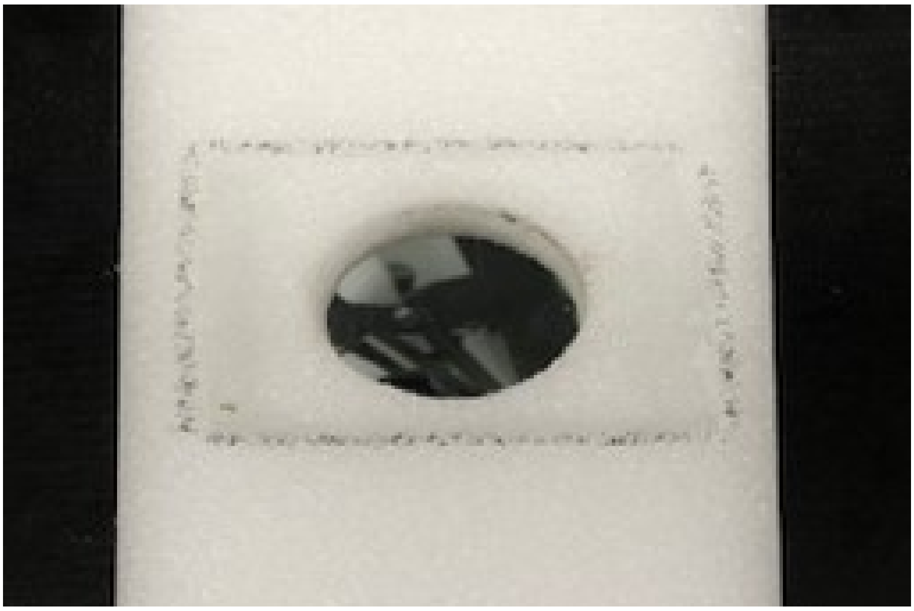


Figure 3.10: Hole to fix the camera

3.4.1. Video treatment

With a Python code, the video acquisition has been done. The first step was to select the interesting part of the image to analyze it, ergo the part where is developed the bubbles trajectories.

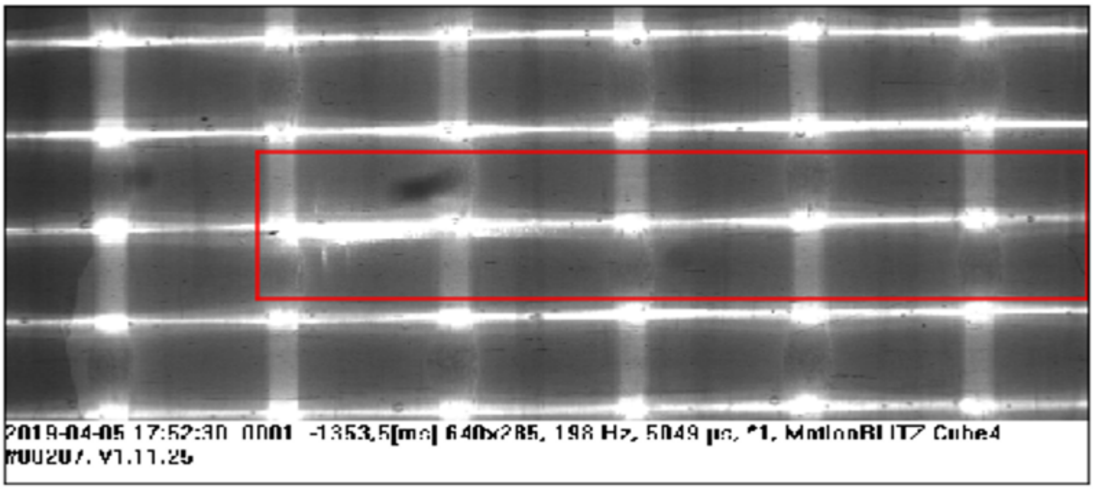


Figure 3.11: Trajectory of the bubbles detected

As it is shown in the Figure 3.12, the changes of light intensity are huge. To achieve the same grade of light in all the frames and avoid flashes, an average has been calculated and applied in all the pictures to be able to detect the bubbles in the same conditions during all the tests. This effect is provoked by the lamp used in the laboratory.

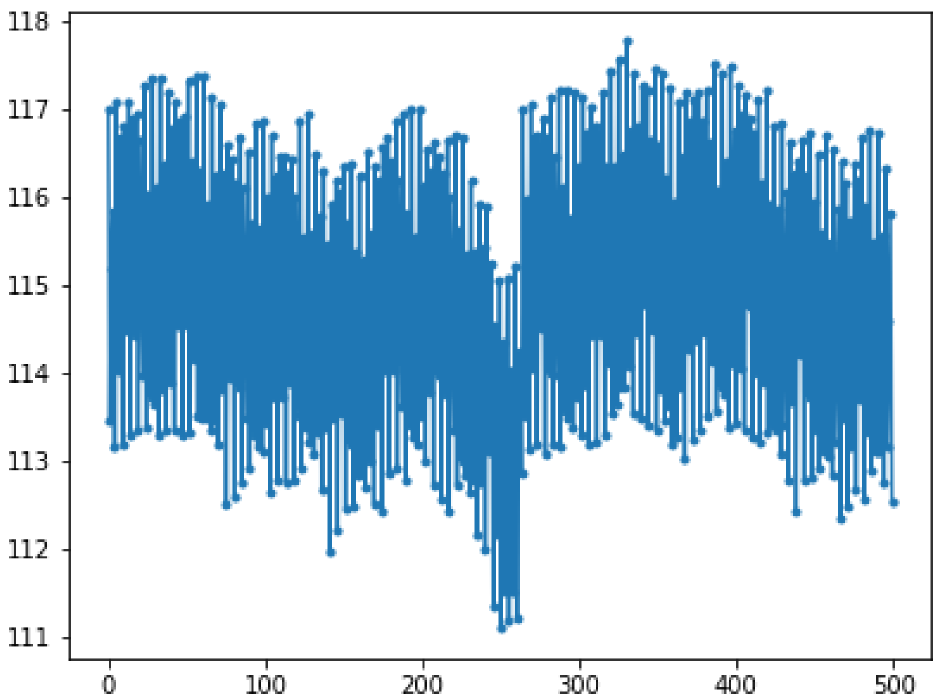


Figure 3.12: Changes of light intensity

Then another average of 500 frames has been done to have a background without bubbles to be able to track the trajectories on the top. The Figure 3.13 reflect the average which should be the same image as before to start the injection.

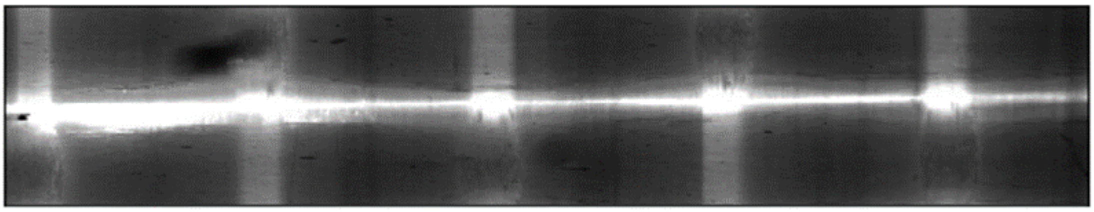


Figure 3.13: Average of images to clarify the image

The first step was reproduce the bubbles in black and white to can distinguish each one (Figure 3.14). Then, the contour was delimited (Figure 3.15) and the center of that was calculated with different colors to distinguish the bubbles.

Figure 3.14: Bubbles detection

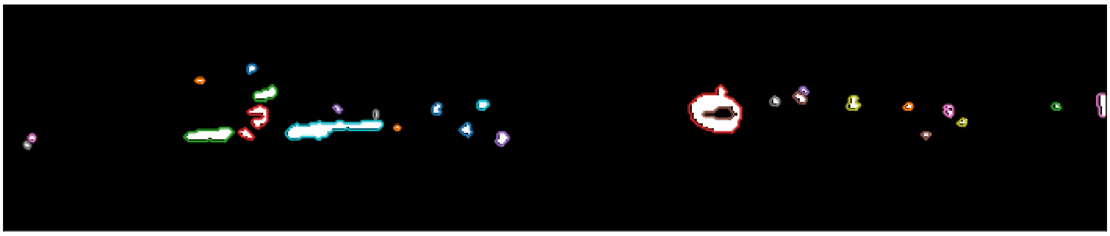


Figure 3.15: Bubbles contour

Once the contour was detected and the center of the bubbles was calculated, the trajectories can be tracked from the center of the bubbles as the Figure 3.16 represent.

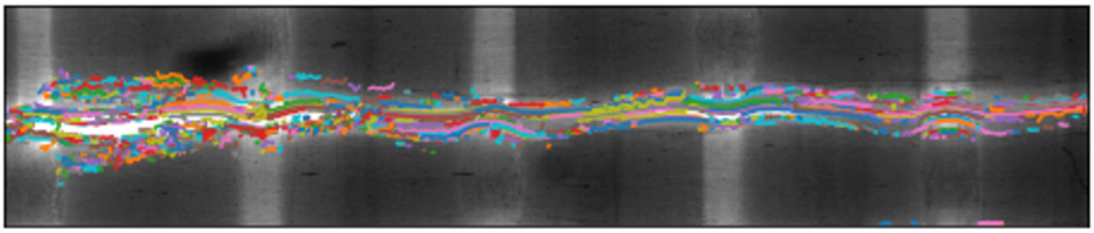


Figure 3.16: Bubbles trajectories with light reflects

There are some issues that can be improved in the high speed video acquisition.

On the one hand, the background is to brightly the python code can not detect well the bubbles and neither the trajectories. This happens for example, when the bubble is next to the tip and the laser light keep off the visibility of the bubbles. The first step to solve it is putting a red filter in the objective of the camera in order to nullify the light of the laser because this makes that we are not able to track the trajectory of the bubbles until the tip.

On the other hand, we could avoid the change of intensity if we try to put another lamp without the flashes explained before.

Finally, near to the laser we can see some short trajectories within the tows and not in the line of the bubbles trajectory. This short trajectories are not real if not is the reflection of the laser light as it is shown in Figure 3.16. As it is mentioned before, when this happens the python code can not distinguish well the bubbles from that reflection and for this reason, the red filter is needed to avoid that.

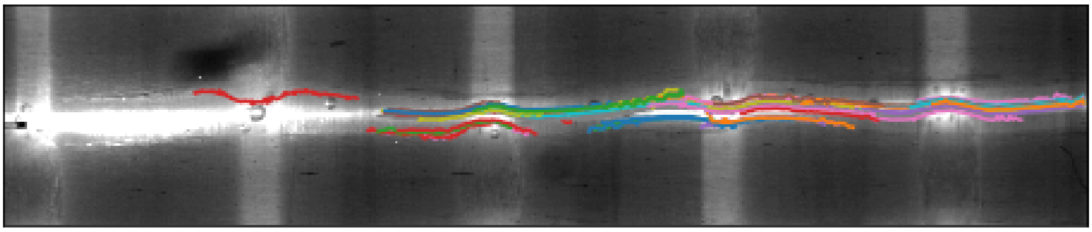


Figure 3.17: Bubbles trajectories only

In the Figure 3.16 next to the laser there are the small trajectories that are from the light reflect. To avoid this type of confusion the code detects when a trajectory is too small to be a bubble and delete it. The result of that part of the code is shown in the Figure 3.17 where next to the tip there are not any trajectory. So, the problem explained before is still because the background is too much brightly next to the tip or laser and the trajectories can not be tracked the only thing improved is to delete the trajectories with no interest to see better and distinguish better the trajectory of the bubbles. In consequence of the fact, a red filter will be needed anyway.

CHAPTER 4. RESULTS

The data recorded by the pc in the lab connected to the signal of the laser, can be processed with three Matlab codes. The first one it is capable to make a plot of the laser signal where appear all the bubbles detected. The second makes a video with consecutive pictures that the camera has been pictured and the final one make a plot with all the bubbles superimposed in order to compare it. Also, with the last code you can know when the bubble appears in the video (in seconds).

The data that we have obtained from the laser it looks like the Figure 4.1 (with an fsamples of 30000 Hz), where it is shown the bubbles detected in one minute. Thanks to this plot you can identify the shape of the bubbles detected and how they have been touched by the tip. This it has been possible for the first Matlab code that provides us the plots (treatment of data).

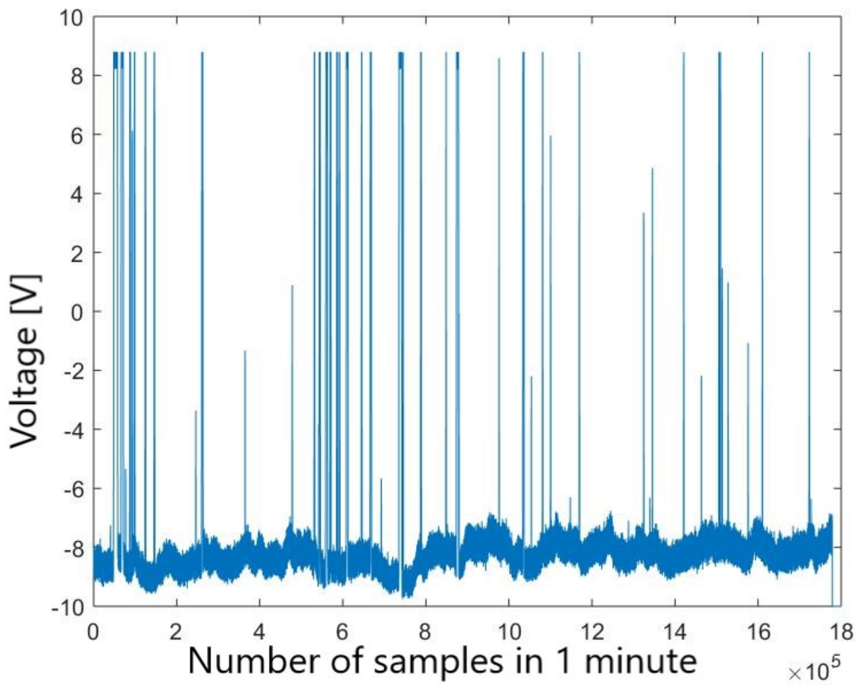


Figure 4.1: Data detected by the laser and processed

The Figure 4.2 is the zoom of one of the bubbles of the Figure 4.1. As the Figure 4.2 shown, the step made for the bubble it is similar to the step that appears in the oscilloscope when the test to validate the functionality of the fibers is done (represented in Figure 2.7). This sample or recording data of the Figure 4.1 is the one used to compare it with the video and obtaining the results.

The first Matlab code, apart of the plots returns the period of the bubble and at which time you can distinguish it in the video.

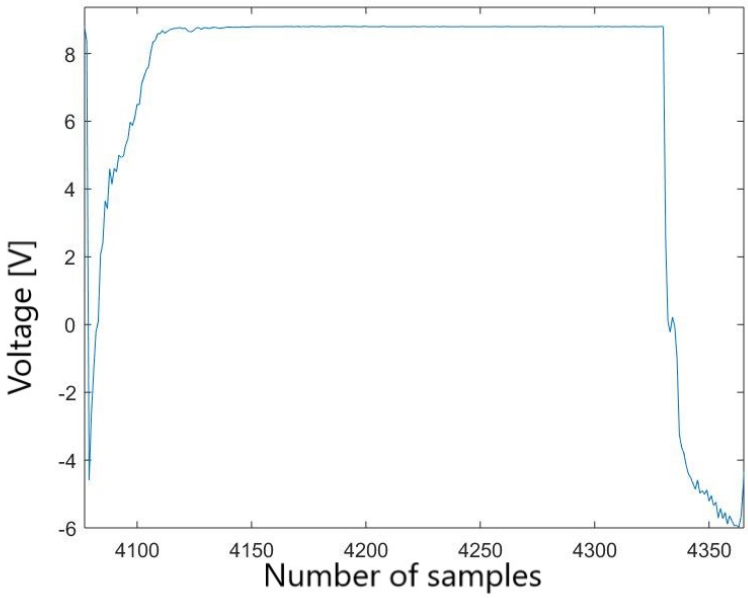


Figure 4.2: Zoom of one single bubble

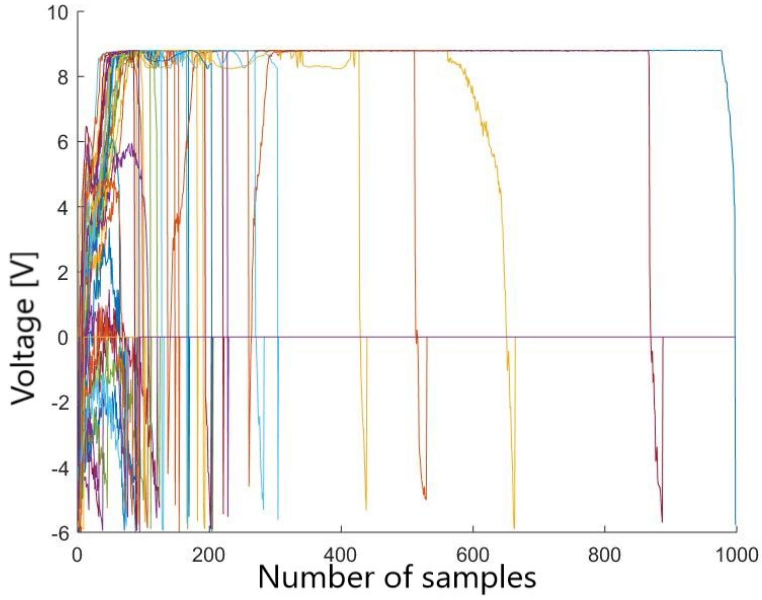


Figure 4.3: Bubbles detected super imposed

The Figure 4.3 helps us to interpret the bubbles that we see in the video. As you can see, different types of bubbles can be distinguished. So, we have divided in three plots to compare it in a more logical way.

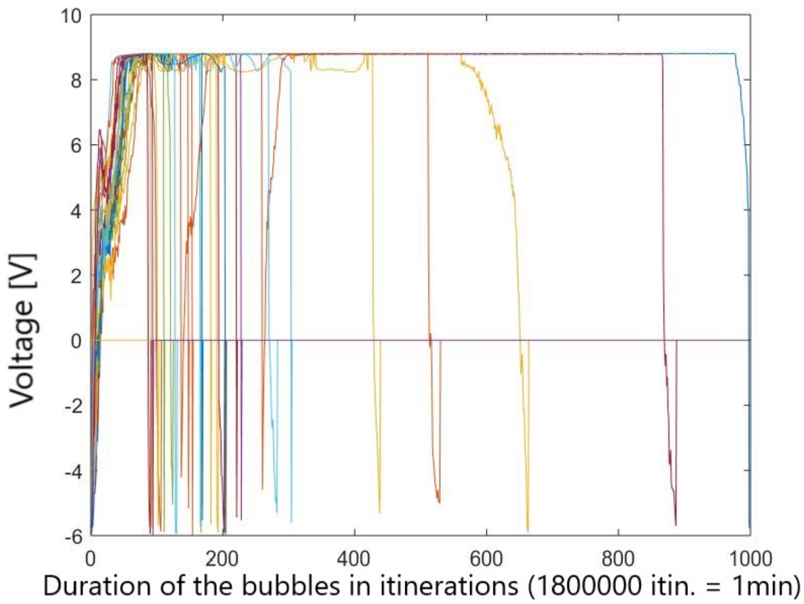


Figure 4.4: Bubbles with good detection

The Figure 4.4 shows the bubbles detected properly (31 bubbles). This bubbles probably has a diameter similar to the diameter of the optical fiber. Also, if the bubble touches directly the tip in front of it, the detection will be better than if the bubbles touches one side of the tip.

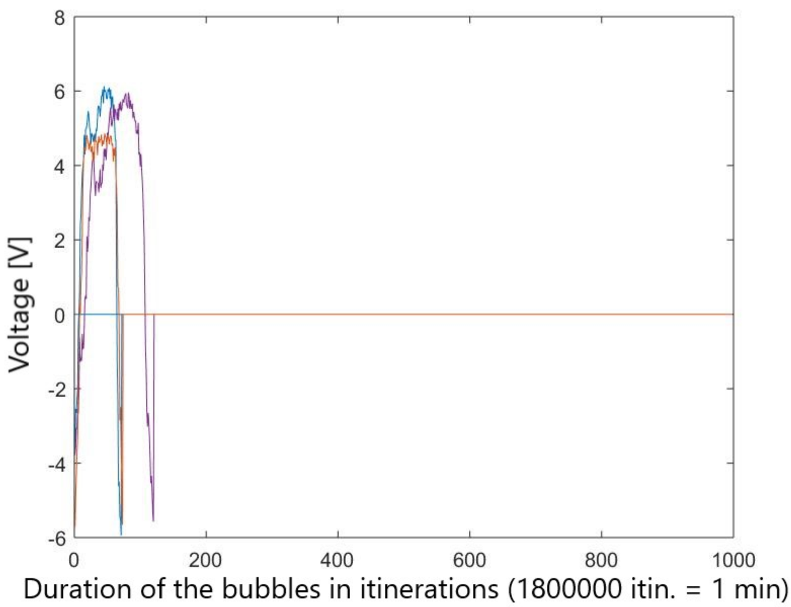


Figure 4.5: Bubbles not totally detected

The Figure 4.5 are the bubbles which have been detected touching one of the sides of the bubble or just the diameter was quite different.

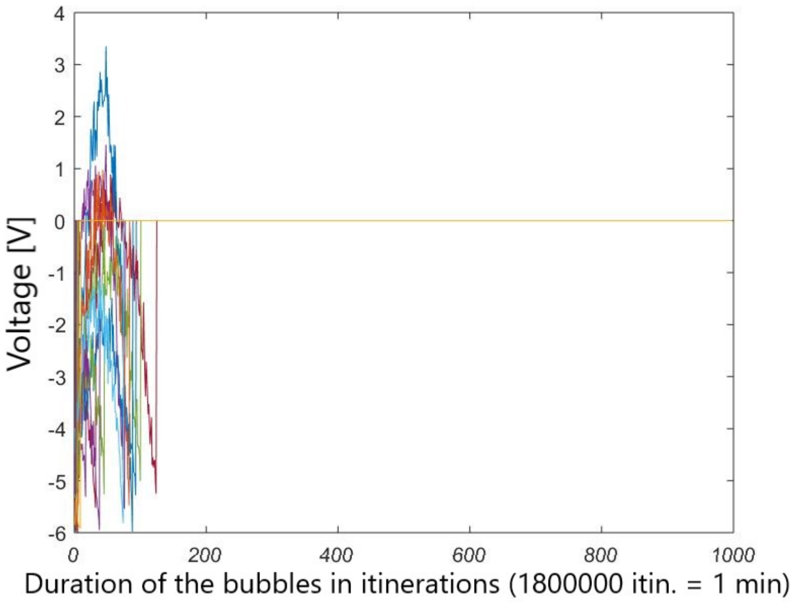


Figure 4.6: Bubbles without a properly detection

Finally, in the last Figure 4.6 appears the bubbles with a bad detection because they are so small or not well detected. For this reason also the duration of the step it is smaller because the detection for the tip is too short.

So, one of the important next steps of this project could be determine better the detection of the bubbles from the tip. If we can see better in the video how the bubbles are detected, may be a great explanation for the types bubbles of the three different plots can be identified. To achieve that the first step is to improve the light next to the tip to see in a good way the detection.

In this three plots it is reflect the duration of the bubbles. The maximum duration are 0.03333s which are from one of the bubbles well detect. And in the minimum duration we have 6.6667e-05s that correspond to a bubble of the last graphic with the characteristics that we have said before. Looking to the video and taking into account only the 31 bubbles properly detected, we can say that only 1 bubble every 4 it is well detected.

4.1. Double conical tip

The velocity is a property to analyze in the bubbles and different methods could be applied to determine it. The double conical tip is one possible solution because that permits to detect the same bubble two times. Thus, the time and the distance between both detection will determine the velocity [15] [16].

The creation of this type of tip is more or less the same process as in the section 2.4. but the tip submerged is bigger. After around 30 minutes, the tip is removed a little bit a certain distance to make the second cone more pronounced. The final structure of the double conical tip has to be as the Figure 4.7 reflect where **d** means the certain distance between the 2 cones. This length is a cylinder an not a cone.

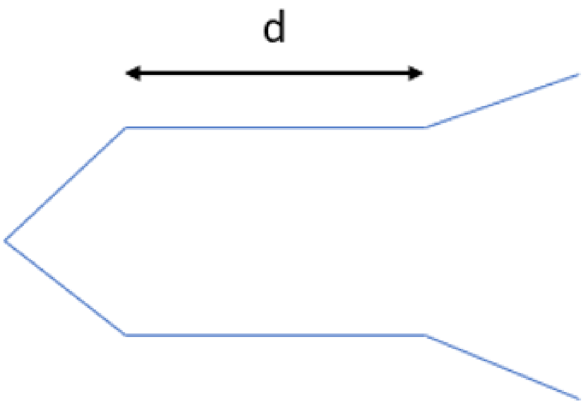


Figure 4.7: Double conical tip scheme

After the creation of this double conical tip, the test of functionality (section 2.6) was done and the results was not the expected ones because the response was a single step (as with the simple conical tip) in order to be a double step because of the 2 conics (as it is explained in [15] [16] with more details).

Therefore, some considerations about the diameter of the fiber or the length between the 2 cones has been done, but another profound research and a lot of tests are needed to obtain good results with these tips. Until the double step is not achieved with the water test, these tips can not be implemented in this project to detect the velocity of the bubbles.

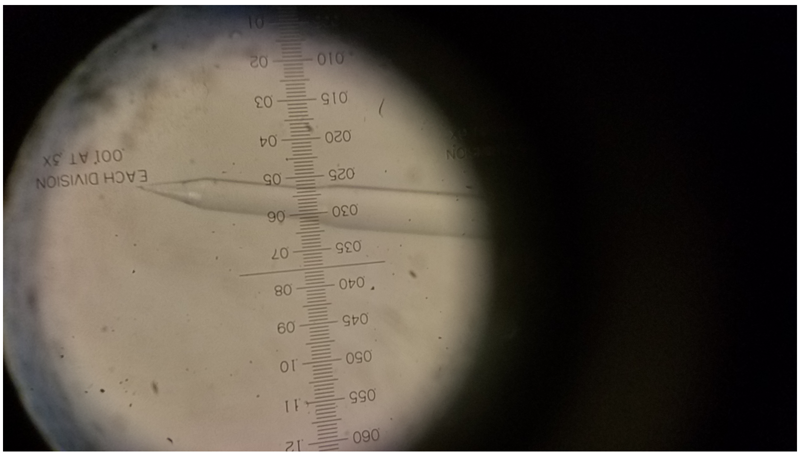


Figure 4.8: Double conical tip

4.2. Future considerations

After research and see what it could be improved in this project some considerations for continue this work could be suggest.

4.2.1. Red filter

To keep away the light next to the tip to see better the trajectories and determine the complete route until the detection, a red filter is needed. This will nullify the red light of the laser and make the background less brightly.

Figure 4.9: Red filter for the camera lens

4.2.2. Python code

Once, the red filter will be applied to camera lens the python code will be check it in order to improve the tracking of the long routes of the bubbles. Until now the trajectories tracked are shown in 3.17.

4.2.3. Develop the research and test with the double conical tip

As the project comment in the section 4.8 the articles [15] [16] do not work in our project, not with the dimensions that the article recommend. Thus, another research and tests will be tried to find the suitable length and diameter for the both cones.

When the functionality test will work, the tip will be applied in the set up to achieve velocities and analyze the new data.

4.2.4. More than one optical fiber

The set up will be test with more than one optical fiber along the fabric to detect if the flow varies in the different distance to the inlet and outlet. Some new results could be obtained.

4.2.5. Pressure sensors

As the article [11] [6] announces a change of pressure between the inlet and outlet has been detected. Therefore, if a pressure sensors are applied, the reasons or some facts could be discovered and to know more about the bubbles behavior. The changes of temperature detected in the article [12] probably could be connected with the changes of pressure.

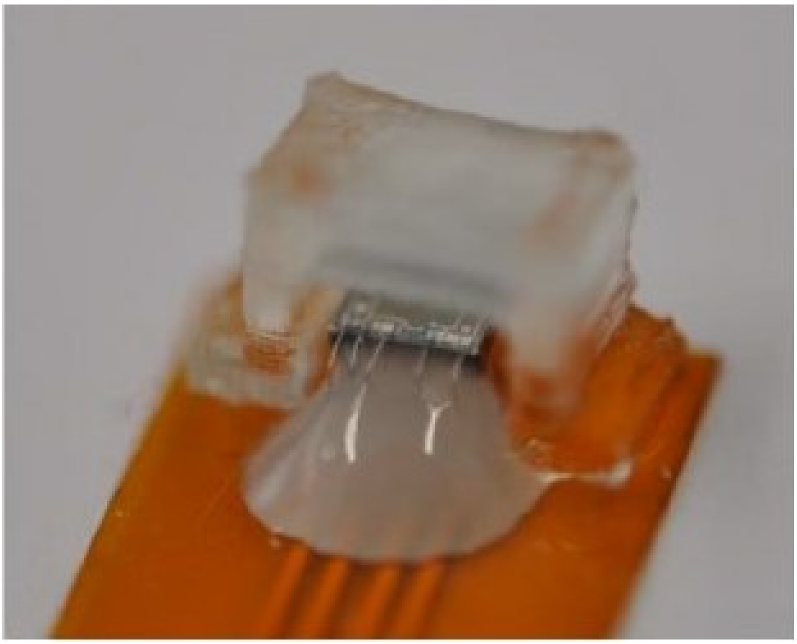


Figure 4.10: Piezoresistive pressure sensor [11]

4.2.6. Simulations to prevent voids

Some programs prevent voids. The issue is that they are too simple and a lot of parameters are not taking into account. So, the program is not realistic. To try to make it better, the idea is to try to put as much inputs, of the different characteristics, as possible to make it with a high precision.

CONCLUSIONS

During the injection of the matrix in a composite material some bubbles are created. In consequence of that, this project develops the experimental study of the diphasic flow during the injection stage of composite processing. A research about the set up creation has been done to achieve a suitable way to perform the injections. Some test about the positioning of the inlet and outlet have been precised. As soon as the configuration was established, the optical fibers was formed. The tip of the optical fibers has to be conical or any bubble will be detected. To originate this tip, acid HF is needed to degenerate the material. Subsequent, fusion was required to have a connection with an oscilloscope. After the construction, some test to verify the functionality was executed. When the optical fibers was applied on the set up, several optical fibers locations was tried until find that the best way to detect the bubbles. The best detection is when the bubbles flow is in the same axis as the optical fiber and when the both diameters are with a similar values. Some data and camera recordings has been precised to the bubbles analysis.

On the one hand, data recording gives an idea of how many bubbles the tip can see in a minute, the detection of each bubble and the different types of bubbles. On the other hand, the film helps to understand and interpret how its happening and approximate its velocity.

What it has been appreciated in the data recorded is that not all the bubbles are detected in the same way because the optical fiber have not the same wide as the fabric. So, the bubbles could cross next to the optical fiber without being detected precisely. Another bubbles are not detected by the tip but you cans ee it in the video. Knowing that the detection has been of 31 bubbles and counting approximately 4 times more in the video, an estimation of 1/4 part of the bubbles are only detected. Furthermore, the matlab code also has given the bubbles duration. On the one side, the maximum duration is of 0.03333s which correspond to a bubbles that has been well detected. On the other side, the minimum duration is of 6.6667e-05s which corresponds to a bubbles that as it is explained before the tip could not see it on a suitable way.

Then, in the video acquisition the bubble trajectory has been tracked to see the route until the tip. This has been performed delimiting the contour of the bubbles and calculating the center of the bubble area. From this point, the center, the trajectory has been tracked.

Some issues has appeared in during the study. The main problem has been the red light of the laser that avoid the tracking of the bubbles until the tip. Also, in the video acquisition the visibility of the bubbles next to the tip is not accurate and the reflect of the light tracks false trajectories.

To improve the study realized some considerations have been suggested. Firstly, to avoid the problem with the red light, a red filter could be applied to nullify the brightly light. Secondly, the python code could be rectified to track longer trajectories. Also, a research of the double conical tip to detect velocities could be deepen to apply it into the set up. Then, more than one optical fibers could be positioned along the set up to see how the flow varies. The variation of the flow is affected for a lot of parameters such as the pressure. Thus, other sensors could be applied too. Finally, a computing program could be developed to make simulations trying to recreate real solutions to see how the bubbles could be avoid and have less voids in the aeronautical pieces.

BIBLIOGRAPHY

[1] Véronique Michaud. *A Review of Non-saturated Resin Flow in Liquid Composite Moulding processes.* Springer Science+Business Media Dordrecht 2016. 3

[2] J. Bouvard, C. Béguin, S. Etienne, D. Scott, L. Bornard. *Characterization of bubble cloud quality and evolution using optical probes*. 19

[3] Chung Hae Park & Woo Il Lee. *Modeling void formation and unsaturated flow in liquid composite molding processes: a survey and review.* Journal of Reinforced Plastics and Composites (2011). xi, 6, 7, 8, 9, 10, 11

[4] Vanita Bhardwaj & Vinod Kumar Singh. *Optical fiber cone taper tip sensor for refractive index measurement.* Indian Journal of Pure & Applied Physics (Vol. 55, May 2017, pp. 345-348). xi, 15, 16

[5] Inès Benito & Benedict Besner. *Procedure to make dual probes.* École Polytechnique Montréal (April 2015). 21

[6] Nihad A. Siddig, Christophe Binetruy, Elena Syerko, Pavel Simacek and Suresh Advani. *A new methodology for race-tracking detection and criticality in resin transfer molding process using pressure sensors.* Journal of Composite Materials 2018, Vol. 52(29) 4087–4103. 35

[7] Alexandros A. Skordos, Panagiotis I. Karkanas and Ivana K. Partridge. *A dielectric sensor for measuring flow in resin transfer moulding.* Measurement Science and Technology 11 (2000) 25-31. 19

[8] H. Grössing, D. Becker, S. Kaufmann, R. Schledjewski, P. Mitschang. *An evaluation of the reproducibility of capacitive sensor based in-plane permeability measurements: A benchmarking study.* eXPRESS Polymer Letters Vol.9, No.2 (2015) 129–142. 19

[9] Y. Yang, G. Chiesura, G. Luyckx, T. Vervust, F. Bossuyt, M. Kaufmann, J. Degrieck, J. Vanfleteren. *Development of a dielectric sensor system for the on-line cure monitoring of composites.* Procedia Technology 15 (2014) 631 – 637. 19

[10] P. Wang, J. Molimard, S. Drapier, A. Vautrin, P. Henrat. *Monitoring the Liquid Resin Infusion (LRI) manufacturing process under industrial environment using distributed sensors.* 19

[11] Maryam Kahali Moghaddam, Arne Breede, Adli Dimassi and Walter Lang. *Piezoresistive Pressure Sensors for Resin Flow Monitoring in Carbon Fibre-Reinforced Composite.* Presented at the Eurosensors 2017 Conference, Paris, France, 3–6 September 2017. xii, 35

[12] TFX-SA- *Resin Transfer Molding (RTM) Process Monitoring Using Heat Flux Sensors.* 35

[13] Suresh G. Advani, E. Murat Sozer, Simon Bickerton, Hubert C. Stadtfeld and Karl V. Steiner. *Use of sensors and simulations to move towards automation of the resin transfer molding process.* University of Delaware, Newark, DE 19716, U.S.A. 19

[14] M. Karaki, A. Hallal, R. Younes, F. Trochu & P. Lafon. *In-plane permeability prediction model for noncrimp and 3D orthogonal fabrics.* https://doi.org/10.1080/00405000.2017.1409327. Dec 2017. xiii, 19

[15] A. Cartellier, E. Barrau. *Monofiber optical probes for gas detection and gas velocity measurements: optimised sensing tips.* International Journal of Multiphase Flow 24 (1998) 1295-1315. 32, 33, 34

[16] A. Cartellier. *Measurement of gas phase characteristics using new monofiber optical probes and real-time signal processing.* Nuclear Engineering and Design 184 (1998) 393–408. 32, 33, 34

APPENDICES

APPENDIX A. MATLAB CODES FOR DATA RESULTS

A.1. Change comma for dot to treat data

```
clear all; clc; close all;
files = dir ('*.txt');
L = length(files);
parfor i=1:L
disp(i)
fichier = files(i).name;
file = memmapfile(fichier, 'writable', true);
comma = uint8(',');
point = uint8('.');
file.Data(transpose(file.Data==comma))=point;
end
```

A.2. Data processing

file$_{n}ame =' test25.txt';$
$fid = fopen(file_{n}ame);$
$header = textscan(fid, repmat('\%s', 1, 7), 1);$
$main_{f}ile = textscan(fid, repmat('\%f', 1, 1));$
$fclose(fid);$

long = length(main$_{f}ile);$
$main_{f}ile_{m}at = cell2mat(main_{f}ile);$

freq$_{a}cq_{c}ell = header(1,7);$
$freq_{a}cq = str2double(freq_{a}cq_{c}ell1);$
$whichfindpeaks - all$
peaks, locmax
$= findpeaks(main_{f}ile_{m}at);$
$i = 1;$
$j = 1;$
$whilei <= length(peaks)$
$ifpeaks(i) <= -6$
$i = i + 1;$
$elseifpeaks(i) > -6$
$ifpeaks(i)\ \ = 0$
$peaks_{b}ubble(j) = peaks(i);$
$pos(j) = locmax(i);$

$j = j+1;$
end
$i = i+1;$
end
end
min, locmin
$= findpeaks((-1)*peaks_{b}ubble);$
$i = 1;$
$j = 1;$
$whilei <= length(min)$
$ifmin(i) <= 5.0$
$i = i+1;$
$elseifmin(i) > 5.0$
$min_{b}ubble(j) = (-1)*min(i);$
$j = j+1;$
$i = i+1;$
end
end
$i = 1;$
$k = 1;$
$j = 1;$
$while(k <= length(peaks_{b}ubble))(i <= length(min_{b}ubble))$
$bubble(i, j) = peaks_{b}ubble(k);$
$j = j+1;$
$ifpeaks_{b}ubble(k) == min_{b}ubble(i)$
$holdon$
$plot(1:1:length(bubble(i,:)), bubble(i,:))$
$duration_{b}ubble(i) = (j*60)/1800000;$
$start_{t}ime(i) = (pos(k)*60)/1800000;$
$ifi == 10$
$pic = peaks_{b}ubble(k);$
$posi = k;$
end
$ifmax(bubble(i,:)) > 8$
$bubble1(i,:) = bubble(i,:);$
$elseifmax(bubble(i,:)) > 4$
$bubble2(i,:) = bubble(i,:);$
$elseifmax(bubble(i,:)) < 4$
$bubble3(i,:) = bubble(i,:);$
end
$j = 1;$
$i = i+1;$
end
$k = k+1;$
end

figure()
plot(1:1:length(peaks$_{b}ubble), peaks_{b}ubble)$

$holdon$
$plot(posi, pic,' r*')$
$figure()$
$plot(1:1:length(main_file_mat), main_file_mat)$
$figure()$
$plot(1:1:length(bubble1), bubble1)$
$figure()$
$plot(1:1:length(bubble2), bubble2)$
$figure()$
$plot(1:1:length(bubble3), bubble3)$
$clearmain_file$

APPENDIX B. PYTHON CODE FOR THE VIDEO ACQUISITION

B.1. Python - Video acquisition

from skimage import data, io, filters
import matplotlib.pyplot as plt
import numpy as np
import os
from time import time
t0 = time()
import cv2
from skimage import exposure
from skimage import feature
from skimage.filters import sobel
from skimage.exposure import histogram
from scipy import ndimage as ndi
from skimage.morphology import watershed
from skimage import measure
from skimage.measure import label, regionprops

image directory
repertoire = os.getcwd()+'
Camera tests
05-04-2019
'
repertoire = os.getcwd()+'
'
output files name file$_out =' test'$
$indexesofimagestotreat$
$image_start = 17500$
$image_end = 18000$
$numberofimagesusedinintensityaveraging$
$nb_image_moy = 500$
$nb_image_total = 1000$

plot the first image
temp = "%05.d" % (image$_start)nom_image =' autosave' + temp +' .bmp'$
$path = repertoire + nom_image$
$image1 = io.imread(path)$
$fig = plt.figure(figsize = (16/2.54, 12/2.54))$
$ax = fig.add_axes([0., 0., 1, 1])$
$ax.imshow(image1, cmap =' gray')$
$ax.set_xticks([])$
$ax.set_yticks([])$

limites de coupure de l'image
coupure1y = 100
coupure2y = 200
coupure1x = 150
coupure2x = 639
x=np.array([coupure1x,coupure2x])
y = coupure1y+0*x
ax.plot(x,y,'r')
y = coupure2y+0*x
ax.plot(x,y,'r')
y=np.array([coupure1y,coupure2y])
x = coupure1x+0*y
ax.plot(x,y,'r')
x = coupure2x+0*y
ax.plot(x,y,'r')

affichage de la premiere image coupee
image1 = image1[coupure1y:coupure2y,coupure1x:coupure2x]
sizex = image1.shape[1]/100.
sizey = image1.shape[0]/100.
fig = plt.figure(figsize=(sizex*2,sizey*2))
ax = fig.add$_{a}xes([0.,0.,1,1])$
$ax.imshow(image1,cmap =' gray')$
$ax.set_{x}ticks([])$
$ax.set_{y}ticks([])$
$fig.savefig(fname =' Figure1.tif',dpi = 100)$

calcul de la moyenne ciblee
liste$_{m}oyenne = np.array([])$
$somme_{i}mages = 0$
$foriinrange(image_{s}tart,image_{s}tart + nb_{i}mage_{m}oy):$
$temp = "\%05.d" nom_{i}image =' autosave' + temp +' .bmp'$
$path = repertoire + nom_{i}image$
$image = io.imread(path)$
$coupuredel'image$
$image = image[coupure1y : coupure2y, coupure1x : coupure2x]$
$image = image.astype(float)$
$liste_{m}oyenne = np.append(liste_{m}oyenne, np.mean(image))$
$somme_{i}mages = somme_{i}mages + image$

affichage de l'image moyenne
image$_{m}oyenne = somme_{i}mages/nb_{i}mage_{m}oy$
$sizex = image_{m}oyenne.shape[1]/100.$
$sizey = image_{m}oyenne.shape[0]/100.$
$fig = plt.figure(figsize = (sizex*2, sizey*2))$

$ax = fig.add_axes([0.,0.,1,1])$
$ax.imshow(image_moyenne, cmap =' gray')$
$ax.set_xticks([])$
$ax.set_yticks([])$
$fig.savefig(fname =' Figure2.tif', dpi = 100)$

tracé de la variation de la moyenne
moyenne = np.mean(liste$_moyenne)$
$fig = plt.figure(figsize = (16/2.54, 12/2.54))$
$ax = fig.add_axes([0.12, 0.12, 0.8, 0.8])$
$ax.plot(liste_moyenne, ' .-')$

correction de la variation de lumiere
liste$_images = []$
$liste_images_corr = []$
$foriinrange(image_start, image_end + 1) :$
$temp = "\%05.d"nom_image =' autosave' + temp +' .bmp'$
$path = repertoire + nom_image$
$image = io.imread(path)$
$coupuredel'image$
$image = image[coupure1y : coupure2y, coupure1x : coupure2x]$
$liste_images.append(image)$
$ratio = moyenne/np.mean(image)$
$image_corr = image * ratio$
$test1 = (image_corr > 255) * 1$
$test2 = (image_corr <= 255) * 1$
$image_corr = image_corr * test2 + 255 * test1$
$liste_images_corr.append(image_corr)$

creation du film comparatif de correction
for i, image in enumerate(liste$_images)$:
$image_corr = liste_images_corr[i]$
$image_jointe = np.append(image, image_corr, axis = 0)$
$image_jointe = image_jointe.astype(np.uint8)$
$height, width = image_jointe.shape$
$size = (width, height)$
$ifi == 0 :$
$out = cv2.VideoWriter(file_out +'_comparaison.avi', cv2.VideoWriter_fourcc(*'DIVX'), 25, size, isColor = False)$
$out.write(image_jointe)$
$out.release()$

ccreation du film des differences a la moyenne
liste$_differences = []$
$fori, image_corrinenumerate(liste_images_corr) :$
$difference = abs(image_corr - image_moyenne)$

$liste_differences.append(difference)$
$ifnp.max(difference) > 20:$
$difference = difference * 254/np.max(difference)$
$difference = difference.astype(np.uint8)$
$height, width = difference.shape$
$size = (width, height)$
$ifi == 0:$
$out = cv2.VideoWriter(file_out +'_difference.avi', cv2.VideoWriter_fourcc(*'DIVX'), 25, size, isColor = False)$
$out.write(difference)$
$out.release()$

for i, image$_corrinenumerate(liste_images_corr):$
$difference = liste_differences[i]$
$imagesegmentation$
$elevation_map = sobel(difference)$
$markers = np.zeros_like(difference)$
$markers[difference < 1] = 1$
$markers[difference > 20] = 2$
$segmentation = watershed(elevation_map, markers)$
$segmentation = ndi.binary_fill_holes(segmentation - 1)$

if i == 0:
fig = plt.figure(figsize=(sizex*2,sizey*2))
ax = fig.add$_axes([0., 0., 1, 1])$
$ax.imshow(segmentation, cmap =' gray')$
$ax.set_xticks([])$
$ax.set_yticks([])$

contour finding
contours = measure.find$_contours(segmentation, 1)$
$nb_bulles = len(contours)$
$print(nb_bulles)$

plot contour
if i == 0:
for n, contour in enumerate(contours):
x = (contour[:, 1])
y = (contour[:, 0])
ax.plot(x,y)
fig.savefig(fname = 'Figure3.tif',dpi=100)

centers matrices
critere$_distance = 3$
$ifi == 0:$
$x_centers = np.zeros([nb_bulles, len(liste_images_corr)])$

$y_centers = np.zeros([nb_bulles, len(liste_images_corr)])$
$forn, contourinenumerate(contours):$
$x_center = np.mean(contour[:, 1])$
$y_center = np.mean(contour[:, 0])$
$x_centers[n, 0] = x_center$
$y_centers[n, 0] = y_center$
$else:$
$previous_{xc}enters = x_centers[:, i-1]$
$previous_{yc}enters = y_centers[:, i-1]$
$forn, contourinenumerate(contours):$
$x_center = np.mean(contour[:, 1])$
$y_center = np.mean(contour[:, 0])$
$distance = ((x_center - previous_{xc}enters) **2 + (y_center - previous_{yc}enters) **2) **0.5$
$ifnp.min(distance) < critere_distance:$
$index_min = np.argmin(distance)$
$x_centers[index_min, i] = x_center$
$y_centers[index_min, i] = y_center$
$else: createnewbubble$
$temp = x_centers[0, :] * 0$
$x_centers = np.vstack([x_centers, temp])$
$y_centers = np.vstack([y_centers, temp])$
$x_centers[-1, i] = x_center$
$y_centers[-1, i] = y_center$

print(x$_centers.shape[0])$

plot last image and all trajectories
fig = plt.figure(figsize=(sizex*2,sizey*2))
ax = fig.add$_axes([0., 0., 1, 1])$
$ax.imshow(image_corr, cmap =' gray')$
$ax.set_xticks([])$
$ax.set_yticks([])$
$foriinrange(x_centers.shape[0]):$
$x_traj = x_centers[i, :]$
$y_traj = y_centers[i, :]$
$x_traj = x_traj[np.where(x_traj > 0)]$
$y_traj = y_traj[np.where(y_traj > 0)]$
$test = len(x_traj)$
$ax.plot(x_traj, y_traj)$
$fig.savefig(fname =' Figure4.tif', dpi = 100)$

plot last image and filtered trajectories
criterion = 50
fig = plt.figure(figsize=(16/2.54,12/2.54))
ax = fig.add$_axes([0., 0., 1, 1])$
$ax.imshow(image_corr, cmap =' gray')$
$ax.set_xticks([])$

$ax.set_yticks([])$
$indices_traj = []$
$foriinrange(x_centers.shape[0]):$
$x_traj = x_centers[i,:]$
$y_traj = y_centers[i,:]$
$x_traj = x_traj[np.where(x_traj > 0)]$
$y_traj = y_traj[np.where(y_traj > 0)]$
$test = np.max(x_traj) - np.min(x_traj)$
$iftest > criterion:$
$indices_traj.append(i)$
$ax.plot(x_traj, y_traj)$

creation du film des trajectoires
liste$_trajectoires = []$
$fori, image_corrinenumerate(liste_images_corr):$
$trajectoire = np.array(image_corr)$
$liste_trajectoires.append(trajectoire)$
$ifnp.max(difference) > 20:$
$difference = difference * 254/np.max(difference)$
$forindiceinindices_traj:$
$x_traj = x_centers[indice,:(i+1)]$
$y_traj = y_centers[indice,:(i+1)]$
$test = np.where(x_traj > 0)[0]$
$iftest.shape[0] > 0:$
$ifnp.max(test) == i:$
$x_traj = x_traj[test]$
$y_traj = y_traj[test]$
$x_traj = x_traj.astype(int)$
$y_traj = y_traj.astype(int)$
$trajectoire[y_traj, x_traj] = 0$

trajectoire = trajectoire.astype(np.uint8)
height, width = trajectoire.shape
size = (width,height)
if i == 0:
out = cv2.VideoWriter(file$_out +'_trajectoire.avi', cv2.VideoWriter_fourcc(*'DIVX'), 25, size, isColor = False)$
$out.write(trajectoire)$
$out.release()$